



Open Research Online

The Open University's repository of research publications
and other research outputs

Ultra deep *AKARI* observations of Abell 2218: resolving the 15 m extragalactic background light

Journal Item

How to cite:

Hopwood, R.; Serjeant, S.; Negrello, M.; Pearson, C.; Egami, E.; Im, M.; Kneib, J.-P.; Ko, J.; Lee, H. M.; Lee, M. G.; Matsuhara, H.; Nakagawa, T.; Smail, I. and Takagi, T. (2010). Ultra deep AKARI observations of Abell 2218: resolving the 15 m extragalactic background light. *Astrophysical Journal Letters*, 716(1) L45-L50.

For guidance on citations see [FAQs](#).

© 2010 The American Astronomical Society

Version: Version of Record

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1088/2041-8205/716/1/L45>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

ULTRA DEEP *AKARI* OBSERVATIONS OF ABELL 2218: RESOLVING THE 15 μm EXTRAGALACTIC BACKGROUND LIGHT

R. HOPWOOD¹, S. SERJEANT¹, M. NEGRELLO¹, C. PEARSON^{1,2,3}, E. EGAMI⁴, M. IM⁵, J.-P. KNEIB⁶, J. KO⁵, H. M. LEE⁵, M. G. LEE⁵,
 H. MATSUHARA⁷, T. NAKAGAWA⁷, I. SMAIL⁸, AND T. TAKAGI⁷

¹ Department of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

² Space Science & Technology Department, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK

³ Department of Physics, University of Lethbridge, 4401 University Drive, Lethbridge, Alberta T1J 1B1, Canada

⁴ Department of Astronomy, The University of Arizona, 933 North Cherry Avenue, Rm. N204, Tucson, AZ 85721-0065, USA

⁵ Department of Physics & Astronomy, FPRD, Seoul National University, Seoul 151-742, Republic of Korea

⁶ OAMP, Laboratoire d'Astrophysique de Marseille, Traverse du Siphon, 13012 Marseille, France

⁷ Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa 229-8510, Japan

⁸ Institute for Computational Cosmology, Durham University, South Road, Durham, DH1 3LE, UK

Received 2009 October 16; accepted 2010 May 7; published 2010 May 20

ABSTRACT

We present extragalactic number counts and a lower limit estimate for the cosmic infrared background (CIRB) at 15 μm from *AKARI* ultra deep mapping of the gravitational lensing cluster Abell 2218. These data are the deepest taken by any facility at this wavelength and uniquely sample the normal galaxy population. We have de-blended our sources, to resolve photometric confusion, and de-lensed our photometry to probe beyond *AKARI*'s blank-field sensitivity. We estimate a de-blended 5σ sensitivity of 28.7 μJy . The resulting 15 μm galaxy number counts are a factor of 3 fainter than previous results, extending to a depth of ~ 0.01 mJy and providing a stronger lower limit constraint on the CIRB at 15 μm of 1.9 ± 0.5 nW m⁻² sr⁻¹.

Key words: galaxies: clusters: individual (Abell 2218) – galaxies: evolution – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

The cosmic infrared background (CIRB) is dominated by the dusty emissions from star-forming galaxies, and therefore traces the dust-enshrouded star formation over the history of the universe. To interpret the CIRB in terms of galaxy formation and evolution models (e.g., Granato et al. 2004; Pearson 2005), it is necessary to resolve the monochromatic backgrounds into their individual galaxies. There is a strong correlation between mid-IR and far-IR star-forming galaxies (Chary & Elbaz 2001; Elbaz et al. 2002), therefore galaxies responsible for the CIRB peak ~ 140 – 200 μm (Dole et al. 2006; Devlin et al. 2009) must also dominate the CIRB at shorter wavelengths, i.e., mid-IR $\lesssim 60$ μm . Recent results from *Spitzer*, SCUBA, and BLAST data have shown, via stacking analysis of 24 μm sources at longer wavelengths, that 24 μm selected populations account for the bulk of 70 μm , 160 μm , and 250 μm backgrounds and also dominate the 350 μm , 450 μm , and 500 μm backgrounds (Dole et al. 2006; Serjeant et al. 2008; Devlin et al. 2009). In contrast, at 850 μm , the 24 μm population only resolves around a quarter of the background (Serjeant et al. 2008). Previous lower estimates of the CIRB at 15 μm , from lensed ISOCAM data (e.g., Metcalfe et al. 2003, hereafter MET03), have successfully resolved the contribution from galaxies highly luminous in the IR, however the greater depth achieved by these data gives a more representative sample of galaxy populations.

Fluctuations from confusion noise, which presents a fundamental limit to blank-field surveys (Condon 1974), are a major challenge for deep IR observations. Exploiting strong gravitational lensing offers a way to probe beyond the inherent blank-field confusion limit (Smail et al. 1997). Where lensing increases the apparent surface area of a background field, the sources within that area are viewed at a lower number density in comparison to the unlensed situation, and the preservation of surface

brightness leads to amplified observed flux densities. Lensing, therefore, offers a twofold confusion-beating effect. Reduction in the observed area leads to source number-density depletion, and both area correction and flux correction are required to recover the true galaxy-number counts (Broadhurst 1995). In addition to faint source confusion below the detection limit, a significant proportion of extractions from a confused image may be blends of two or more sources, so photometric de-blending is required (Rodighiero et al. 2006).

In this Letter, we present new 15 μm galaxy number counts and 15 μm integrated light (IGL₁₅) estimate. In Section 2, we summarize the *AKARI* data and data reduction. A data analysis description is given in Section 3, and the results are presented in Section 4 and discussed in Section 5.

Throughout this Letter, we assume flat Λ CDM cosmology with $\Omega_M = 0.3$ and $H_0 = 70$ km s⁻¹ Mpc⁻¹.

2. DATA ACQUISITION AND ANALYSIS

2.1. Data

AKARI 15 μm observations of A2218 were taken with the L15 filter of *AKARI*'s IRC (*AKARI*: Murakami et al. 2007; IRC: Onaka et al. 2007). The IRC has a wider field of view of $10' \times 10'$ in comparison to Infrared Array Camera (IRAC) aboard *Spitzer*, offering fuller coverage from 2 to 24 μm . Nineteen pointings were acquired with the astronomical observation template IRC05, which is designed for deep observations and performs no dithering, however a nominal positional offset was applied in between pointings.

2.2. Data Reduction

The data were reduced using the standard IRC pipeline, version 20070912 (Lorente et al. 2008, hereafter IRC-DUM). During the pipeline, each pointing was divided into its constituent

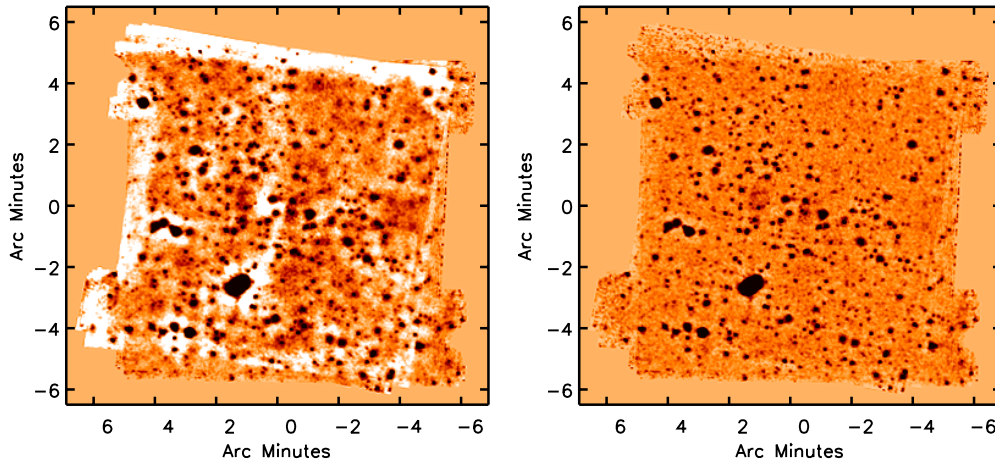


Figure 1. Comparison between the L15 image combined post-pipeline (left) and the L15 image combined after the further reduction (right). The same pixel scaling was used for both. The low-frequency background structure evident in the post-pipeline image is successfully removed by the additional reduction.

(A color version of this figure is available in the online journal.)

long and short exposures. The short exposures do not significantly add to the depth or quality of the final frame, so they are discarded. Each long exposure is 16.5 s, and up to 30 were average-combined per pointing, giving 19 reduced frames. We used optical data to register the frames' astrometry.

The frames can be grouped based on the relative scanning direction of the IRC with A2218. An interval of roughly 6 months between the 10th and 11th pointings gave $\sim 180^\circ$ difference in the orientation of the first 10 frames (hereafter L15-A) and the final 9 frames (hereafter L15-B). This time interval led to an increase of bad pixels in the L15-B data, due to detector degradation. The L15-B data also suffer more severely from scattered light, a problem noted in the IRC-DUM. The scattered light is partially addressed by the pipeline, but remains an issue for several of the frames. A low-frequency sky noise is experienced by all post-pipeline frames. Combining the post-pipeline frames gives a significantly uneven background structure, which is detrimental to subsequent photometry. We therefore subtracted a median-filtered sky model, generated per frame, using a kernel width of $21''.5$. A comparison of photometry taken for the image combined post-pipeline and the image combined after the additional sky subtraction showed good agreement at the bright end and a systematic shift at the faint end, attributable to the sky structure present in the non-filtered image. We, therefore, concluded that the median-sky subtraction removes systematics associated with the extended sky structure, without detriment to source photometry.

The final frames were average combined, giving an image (hereafter L15 image) with total integration time of 8460 s, full width at half-maximum (FWHM) of the point-spread function (PSF) estimated at $5''.9$ and a pixel scale of $2''.3$. Figure 1 shows the post-pipeline combined image compared to the L15 image.

3. ANALYSIS

3.1. Source Extraction

A 5σ source extraction was performed on the L15 image, with DAOFIND (Stetson 1987). Combining the L15-A frames and the L15-B frames into two “half-images” gave the means for a robust reliability check. Each source was examined individually in the “half-images,” and those appearing at corresponding coordinates within both images were assumed to be real.

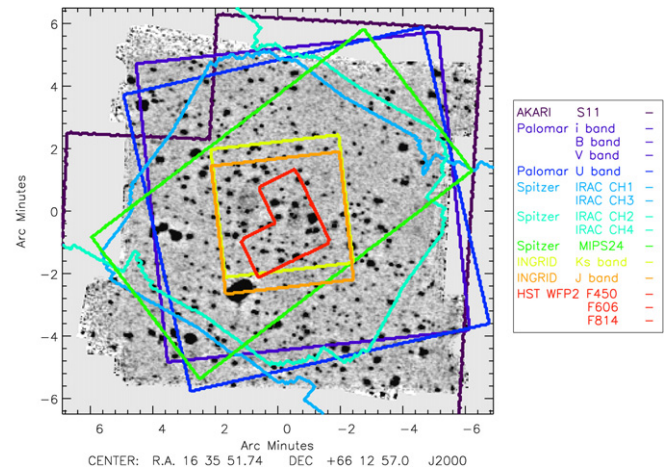


Figure 2. L15 image overlaid with contours indicating the multi-wavelength coverage of A2218.

(A color version of this figure is available in the online journal.)

3.2. Sensitivity

To estimate the map sensitivity we took aperture photometry at random positions, excluding the edges. An aperture radius of $5''.9$ was used, and full flux densities were obtained using an aperture correction of 1.44 (see Section 3.7) and the IRC-DUM ADU-to- μJy conversion factor of $1.69 \mu\text{Jy ADU}^{-1}$. Fitting a Gaussian, with standard deviation $8.3 \mu\text{Jy}$, to the resulting distribution gave a 5σ sensitivity estimate of $41.7 \mu\text{Jy}$. For the PSF-fitted catalog (see Section 3.5), the sensitivity was estimated by comparing the input and output photometry for artificial sources introduced to the L15 image, giving a 5σ sensitivity of $28.7 \mu\text{Jy}$.

3.3. Multi-waveband Counterparts

We have multi-waveband coverage of A2218 taken by several facilities: *Hubble Space Telescope* (HST) WFP2 F450, F606, and F814, Palomar 200 inch Hale u' , V , B , i' and WHT's INGRID Ks and J (Smail et al. 2001a; Ziegler et al. 2001); *Spitzer* IRAC Ch 1 to 4 and MIPS $24 \mu\text{m}$ (E. Egami 2010, in preparation); *AKARI* S11 (Ko et al. 2009). Figure 2 illustrates the A2218 coverage provided by this data set.

To help identify blended sources within the extracted catalog, a multi-waveband counterpart identification was performed. Potential counterparts for each L15 source were identified via a centroid search within a radius of $3''.8$ ($0.64 \times \text{FWHM}$) from the L15 centroid. For each source, a comparison of postage-stamp images across the available wavebands was performed to identify the main counterpart (brightest) plus subsidiary counterparts (less bright) and extra sources in the field not initially identified via the 5σ extraction and within a radius of $18''.0$.

3.4. Field Distortion

A positional discrepancy between the L15 image and the counterpart images was identified during the counterparting process giving a spatially varying PSF in the L15 image. Cubic polynomial coefficients were derived to map the L15-B frames onto the L15-A frame, and the resulting frames onto the Palomar and IRAC images. The L15 image was recombined and the empirical PSF was reconstructed, using PSTSELECT and PSF of the DAOPHOT package (Stetson 1987), and showed no spatial variability. The source catalog was then re-centered and the counterparting rerun.

3.5. De-blending and PSF Fitting

Simultaneous PSF fitting was performed on the L15 image using the full post-counterparting catalog, which offers the benefit of positional priors. Constructing a reliably representative empirical PSF from a confused image is challenging, so we used all suitable sources available to statistically reduce noise in the PSF's tail. The PSF was refined following the iterative method outlined in the DAOPHOT2 manual (Stetson 2000). The PSF radius was set to $17''.9$, which collects approximately 100% of the flux for non-extended sources according to the IRC-DUM and a plot of normalized pixel value as a function of radius, for sources in the L15 image. The resulting empirical PSF was used to CLEAN (Högbom 1974) the L15 image with ALLSTAR (Stetson 1987), giving a PSF-fitted source catalog of 918 sources. The increase in the number of sources corresponds to a $\sim 40\%$ improvement in the completeness (see Section 3.6).

3.6. Completeness

Two separate Monte Carlo completeness tests were run to represent the 5σ catalog and PSF-fitted catalog. The first test used the established method of adding randomly placed artificial sources to the L15 image, separated from the 5σ catalog, then performing an extraction on the results followed by aperture photometry of the extracted sources. The artificial sources were randomly scaled within defined flux density bins covering the source catalog's flux range. For the first test, the artificial source positions were generated with sufficient separation to avoid self-confusion. The $25''$ minimum separation was derived by plotting normalized pixel values as a function of radius for bright well-separated sources. Twice the radius where the median pixel values disappear into the background was chosen. This test was repeated until around 20,000 sources per bin were achieved. The first test was adapted to represent the PSF fitting of a photometrically confused environment. Input positions were still generated randomly and kept at a distance from known source positions, although this limiting separation was reduced to $19''$. A self-separation was imposed, but only to reject equal random positions. To reflect the use of positional priors and the re-centering carried out by ALLSTAR, the randomly generated

input positions were used as the ALLSTAR input rather than the extracted positions. This second test was repeated until around 30,000 sources per bin were achieved.

Completeness was defined as the fraction of recovered sources per bin. The results of the first tests show that the L15 image is 10%, 50%, and 90% complete down to $20.2 \mu\text{Jy}$, $30.7 \mu\text{Jy}$, and $46.8 \mu\text{Jy}$, respectively. For the second test, the L15 image is 10%, 50%, and 90% complete down to $12.2 \mu\text{Jy}$, $20.0 \mu\text{Jy}$, and $31.5 \mu\text{Jy}$, respectively.

3.7. Multi-waveband Photometry

HST photometry was obtained from the published catalog of Smail et al. (2001b). IRAC aperture photometry was taken with an aperture radius of $2''.4$ and an annulus of radii $14''.6$ and $24''.4$, and the published IRAC aperture corrections were applied. For the remaining counterpart images, aperture photometry was taken and a growth-curve aperture correction method was employed (Howell 1989; Stetson 1990). For each image, a median growth curve was empirically constructed using aperture photometry taken for bright and well-separated sources, with concentric apertures of increasing radii. The u' to Ks images were better represented by two growth curves, one for point-like sources and the other for elliptical sources, which are not significantly extended. Aperture corrections were chosen on a source-by-source basis to minimize contamination from neighbors. For the L15 image an aperture correction for a radius of $5''.9$ was derived, using the empirical PSF and a comparison of the PSF-fitted photometry and aperture photometry.

3.8. Photometric Redshifts

Two codes that utilize a minimum χ^2 spectral energy distribution (SED) fitting method were applied to estimate photometric redshifts for L15 sources with photometry coverage in four or more filters, shortward of $11 \mu\text{m}$. EaZy (Brammer et al. 2008) is suitable for data sets with few or biased spectroscopic redshifts (z_{spec}), such as the z_{spec} available for the L15 catalog, which are mainly biased at the cluster redshift of 0.18. The EaZy theoretical SED templates are based on semi-analytical models, and a linear combination of templates can be fitted simultaneously. IRAC photometry was included due to EaZy's ability to fit photometry up to IRAC CH4, however this is dependent on redshift. EaZy gives the option to apply priors aimed at breaking the template color degeneracies seen with increasing redshift. Our spectra were also fitted using the photometric code of Negrello et al. (2009, hereafter N09). This code is uniquely optimized for fitting mid-to-far-infrared polycyclic aromatic hydrocarbon (PAH) and silicate features seen in starburst SEDs. For sources with strong mid-IR PAH features, the comparison of N09 and EaZy redshifts was consistent with a slope of 1. A robust catalog of photometric redshifts was constructed using a visual triple-check per source to reject unreliable estimates. The best SED fits from EaZy and N09 and the source morphology were visually compared, in context of the redshift estimate and probability of the minimum χ^2 . The redshift catalog was constructed primarily from EaZy estimates. For sources with pronounced mid-IR features and reliable EaZy and N09 estimates, not in agreement within their 1σ errors, the N09 estimates were used when clearly providing additional constraint from fitting to mid-IR photometry. Cluster members were identified from spectroscopic redshifts or during the triple comparison, from their typical SED and elliptical morphology. Cluster members represent 16% of the total catalog, including

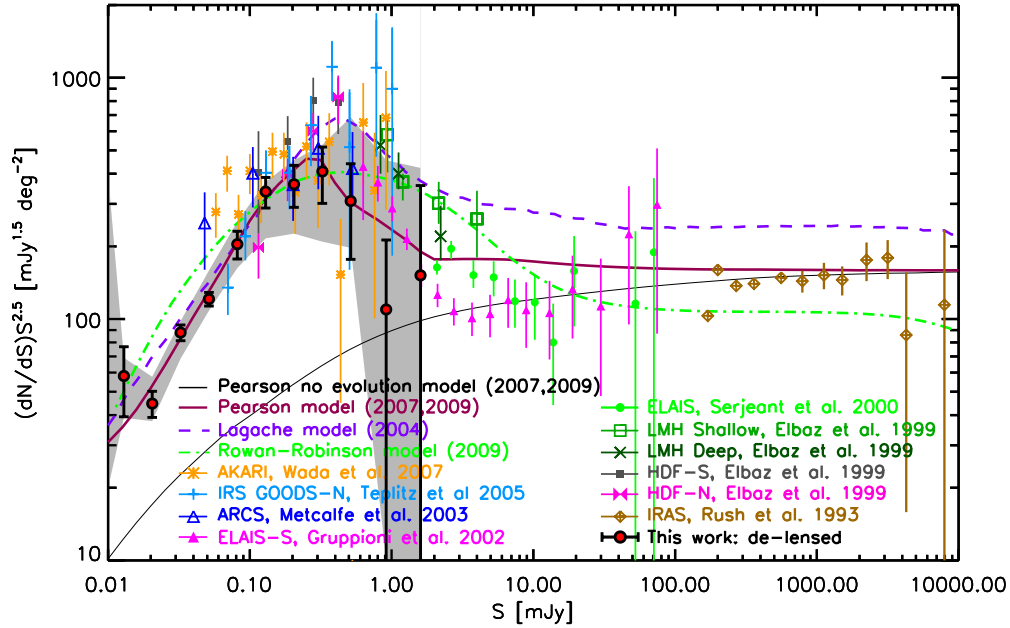


Figure 3. Euclidean-normalized differential galaxy number counts. The L15 de-lensed counts are compared to the P10 model counts and no-evolution model (Pearson et al. 2007; C. Pearson 2010, in preparation), the Rowan-Robinson (2009) model, the Lagache et al. (2004) model, *IRAS* counts from Rush et al. (1993; shifted from 12 μ m), *ISO* counts from Elbaz et al. (1999), Serjeant et al. (2000; re-calibrated following Väisänen et al. 2002), Gruppioni et al. (2002) and Metcalfe et al. (2003), *IRS* counts from Teplitz et al. (2005), and *AKARI* counts from Wada et al. (2007). The gray shaded area represents the 2σ bootstrapped confidence interval for the L15 counts. Note the good agreement of the faint end of the L15 counts with the Pearson and Lagache models.

(A color version of this figure is available in the online journal.)

all significantly extended sources. All cluster members were subsequently removed. Thirty-one percent of the remaining catalogs are without a redshift estimate, either due to a lack of multi-wavelength coverage or unreliable photometric estimate. For these sources a redshift of 1.04 ± 0.67 was assigned, which is the median of the redshift catalog with 1σ errors. Substituting a value of 2.0 or 3.0, in place of the median redshift value, gave no significant difference for the resulting number counts.

4. RESULTS

4.1. A2218 Mass Model

Magnification corrections (μ) were obtained using LENSTOOL (Jullo et al. 2007), which required as input a mass model of A2218 and the positions and redshifts for all sources beyond the cluster distance. A pseudo-isothermal elliptical mass model is assumed for the mass distribution of the A2218 cluster members. Strongly lensed arcs and arclets are used to constrain the mass distribution and total mass of the cluster (Elíasdóttir et al. 2007; Kneib et al. 1996). Spectroscopy of arclets has been used to test this model for reliability (Ebbles et al. 1998).

4.2. Galaxy Number Counts

Flux densities (S) were corrected prior to counting as $S_{\text{true}} = \frac{S_{\text{obs}}}{\mu}$. Corrections for depletion and incompleteness were applied to individual sources during counting, assuming the relation $n_{\text{true}} = \frac{\mu}{C(S_{\text{obs}})}$, where n_{true} is the true number of sources and the completeness (C) is a function of S_{obs} (rather than S_{true}). De-lensed number counts over bin dS are then obtained as $\frac{dN}{dS} = \Sigma n_{\text{true}}$. The amplification ($\frac{1}{\mu}$) distribution ranges from 1.0 to 24 and has a median of 1.2, which reflects the wide area of A2218 covered and the decrease of amplification as a function of radius from the center of the core. The μ distribution

obtained was not found to change significantly with the variation of redshifts within the L15 redshift distribution.

Figure 3 shows our Euclidean-normalized differential number counts, in comparison to a compilation of previous work and predictions based on galaxy evolution models. The median completeness per bin is 100% down to the faintest three bins, which have median completeness corrections of 26%, 70%, and 96%, respectively. Our L15 counts extend the faint end of observed counts down to ~ 0.01 mJy, which is a factor of 3 fainter in comparison to the ISOCAM (Cesarsky et al. 1996) lensing survey counts of MET03. Below 0.2 mJy the L15 counts present a steep sub-Euclidean slope of -1.6 , which agrees with the faint slope of Elbaz et al. (1999). The no-evolution model is strongly excluded by all available data and there is a general consensus on a significant evolutionary bump, which peaks around 0.2–0.4 mJy. The comparably steep slope of the L15 counts brighter than the “bump” is the result of de-blending. The Pearson 2007/2010 model (hereafter P10) predicts that the populations dominating the 15 μ m counts “bump” are starbursts ($L < 10^{11} L_{\odot}$) and luminous infrared galaxies (LIRG; $10^{11} L_{\odot} < L < 10^{12} L_{\odot}$), with redshift distributions peaking at $z = 0.5$ and $z = 1.2$, respectively. At a mean redshift of 0.8, in the bump, $S_{15} = 0.3$ mJy corresponds to $\sim 4 \times 10^{11} L_{\odot}$ for an M82 SED.

4.3. Bootstrapping

Confidence intervals for the differential counts were derived by bootstrapping within the photometric and redshift errors, as these are the dominant source of uncertainties for the counts. The L15-flux population was re-sampled without bias for the lensed-source catalog. Each sample was randomly assigned flux densities and redshifts within the respective 3σ errors, and de-lensed with recalculated magnification corrections. Thirty thousand re-sampled populations were generated and differential

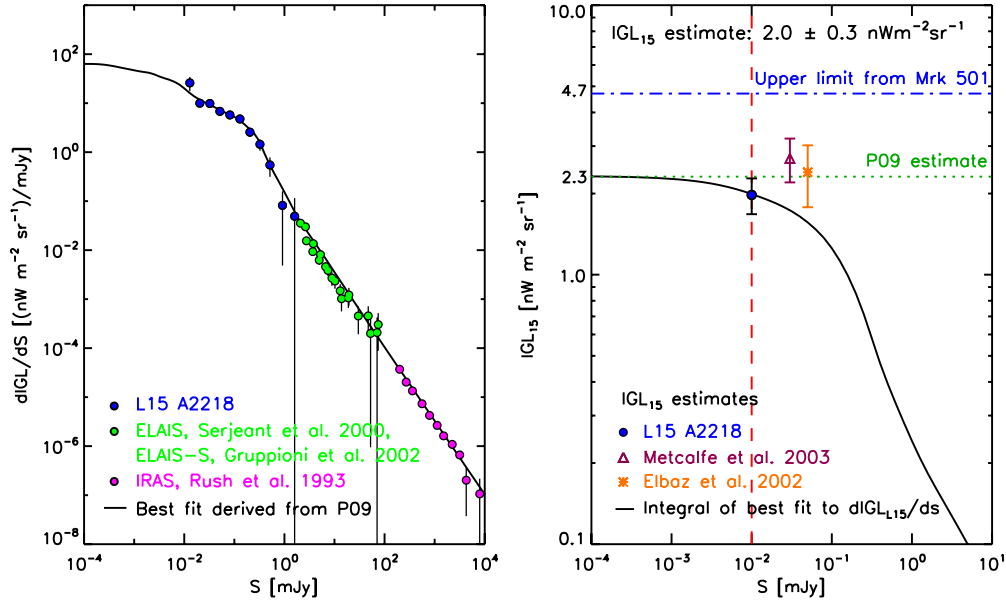


Figure 4. Differential contribution to the IGL₁₅ as a function of flux density (left). Data shown are the L15 data, data from Serjeant et al. (2000), Gruppioni et al. (2002), and Rush et al. (1993). The black line represents the best fit of the P10 model to the L15 data. IGL₁₅ estimates as a function of flux density (right). The L15 estimate is limited to 0.01 mJy, illustrated by the dashed red line. The Elbaz et al. (2002) and Metcalfe et al. (2003) estimated limits are 0.05 and 0.03 mJy, respectively. The IGL₁₅ upper limit was derived from γ -ray emission of Mrk 501 (Renault et al. 2001).

(A color version of this figure is available in the online journal.)

Table 1

Lensed ($\frac{dN(S_{\text{obs}})}{dS_{\text{obs}}}$) and De-lensed ($\frac{dN(S_{\text{true}})}{dS_{\text{true}}}$) Differential Number Counts, corrected for Incompleteness, and the Associated Bootstrapped Median Number Counts and Standard Deviation for the De-lensed Counts

| Bin _L (mJy) | $\frac{dN(S_{\text{obs}})}{dS_{\text{obs}}} (mJy^{-1} \text{deg}^{-2})$ | $\frac{dN(S_{\text{true}})}{dS_{\text{true}}} (mJy^{-1} \text{deg}^{-2})$ | $\frac{dN(S_{\text{true}})}{dS_{\text{true}}} \text{ bootstrap} (mJy^{-1} \text{deg}^{-2})$ | $\sigma_{\text{bootstrap}} (mJy^{-1} \text{deg}^{-2})$ |
|------------------------|---|---|---|--|
| 1.00E-02 | $(4.37 \pm 0.98)E+06$ | $(3.06 \pm 0.99)E+06$ | 2.76E+06 | 3.54E+05 |
| 1.59E-02 | $(8.60 \pm 0.58)E+05$ | $(7.44 \pm 0.92)E+05$ | 7.71E+05 | 7.13E+04 |
| 2.51E-02 | $(3.61 \pm 0.81)E+05$ | $(4.63 \pm 0.35)E+05$ | 4.27E+05 | 3.28E+04 |
| 3.98E-02 | $(2.23 \pm 0.12)E+05$ | $(2.02 \pm 0.13)E+05$ | 2.16E+05 | 1.80E+04 |
| 6.31E-02 | $(9.42 \pm 9.47)E+04$ | $(1.08 \pm 0.14)E+05$ | 1.06E+05 | 1.03E+04 |
| 1.00E-01 | $(4.44 \pm 0.52)E+04$ | $(5.62 \pm 0.81)E+04$ | 4.73E+04 | 5.70E+03 |
| 1.59E-01 | $(1.93 \pm 0.27)E+04$ | $(1.90 \pm 0.38)E+04$ | 1.73E+04 | 2.73E+03 |
| 2.51E-01 | $(7.17 \pm 1.31)E+03$ | $(6.81 \pm 1.79)E+03$ | 5.92E+03 | 1.22E+03 |
| 3.98E-01 | $(2.56 \pm 0.62)E+03$ | $(1.62 \pm 0.69)E+03$ | 2.24E+03 | 6.00E+02 |
| 6.31E-01 | $(2.47 \pm 1.23)E+02$ | $(1.37 \pm 1.29)E+02$ | 2.65E+02 | 1.37E+02 |
| 1.20E+00 | $(0.00 \pm 0.00)E+00$ | $(4.68 \pm 6.35)E+01$ | 4.39E+01 | 4.01E+01 |

Note. Lower bin limits are given.

counts were taken for each. Confidence intervals were calculated using the median and standard deviation of the re-sampled counts. The gray shaded region of Figure 3 shows the resulting 95% confidence interval. The divergence of the bootstrapping below 0.02 mJy shows that the upturn of the counts in the final bin is not statistically significant. The differential number counts and the bootstrapped standard deviation are presented in Table 1.

4.4. 15 μ m Integrated Galaxy Light

The IGL₁₅, a lower limit for the CIRB₁₅, can be obtained by integrating the flux per unit area for the corresponding monochromatic number counts. The differential contribution to the IGL₁₅ is given by

$$\frac{dIGL}{dS} = \frac{dN}{dS} \left(\frac{S}{10^{20}} \right) \nu_{15}$$

(e.g., Elbaz et al. 2002) where $1 \text{ mJy} = \frac{1}{10^{20}} \text{ nW m}^{-2} \text{ sr}^{-1}$ and ν_{15} is the frequency of the 15 μ m photons.

Using the counts of Serjeant et al. (2000; re-calibrated following Väisänen et al. 2002), Gruppioni et al. (2002), Rush et al. (1993), and the L15 counts, giving a flux range of 0.01–10,000 mJy, we estimate $IGL_{15} = 1.9 \pm 0.5 \text{ nW m}^{-2} \text{ sr}^{-1}$. The lensed fields observed by ISOCAM (including A2218) produced 15 μ m counts down to 0.03 mJy and a lower limit estimation for the IGL₁₅ of $2.7 \pm 0.62 \text{ nW m}^{-2} \text{ sr}^{-1}$ (MET03, and references therein). These estimates agree within the errors. Using the lower flux limit of MET03, and our methodology, gives an IGL₁₅ of $1.6 \pm 0.38 \text{ nW m}^{-2} \text{ sr}^{-1}$, which is marginally consistent ($\sim 2\sigma$) with the MET03 estimate. The P10 model provides an excellent fit to the whole of our data. Integrating over the full flux range of the P10 model gives a predicted IGL₁₅ of $2.3 \text{ nW m}^{-2} \text{ sr}^{-1}$. If we assume the shape (but not the normalization) of the P10 counts, we derive a slightly better estimate of $IGL_{15} = 2.0 \pm 0.4 \text{ nW m}^{-2} \text{ sr}^{-1}$ at $\geq 0.01 \text{ mJy}$ (see Figure 4). In comparison to the MET03 result, which resolved $\sim 70\%$ of the CIRB₁₅ into individual galaxies, we are $3\times$ deeper and resolve $87\% \pm 13\%$ and, whereas the *Infrared Space Observatory (ISO)* surveys mainly sample galaxies with

luminosities \geq LIRG, we are probing the more normal galaxy populations.

5. DISCUSSION AND CONCLUSIONS

From our de-blended and de-lensed $15\ \mu\text{m}$ counts we have derived an IGL₁₅ estimate of $2.0 \pm 0.4\ \text{nW m}^{-2}\ \text{sr}^{-1}$, down to $\sim 0.01\ \text{mJy}$. We conclude that, with respect to the P10 model, the AKARI $15\ \mu\text{m}$ data are consistent with having resolved the whole of the predicted IGL₁₅. Assuming no radical change between the IR SED of high-redshift galaxies and those resolved at $15\ \mu\text{m}$ with median redshift of 1.0 (Elbaz et al. 2002), then the galaxies resolved by these data represent the bulk of galaxies dominating CIRB peak.

Figure 4 suggests that in order to resolve 100% of the CIRB₁₅, future observations need to probe depths in the region of 1 mag fainter than the sensitivity limit achieved by this survey, down to at least $S_{15} = 1\ \mu\text{Jy}$. The first possible direct measurement constraints of the CIRB₁₅ will come from JWST or SPICA (Gardner et al. 2006; Nakagawa 2004).

Fifteen micron stacking analysis of Herschel/SPIRE and PACS A2218 data will address how representative $15\ \mu\text{m}$ selected galaxies are of the galaxy populations responsible for the CIRB at its peak.

We thank the anonymous referee for insightful and constructive comments. We thank the Great Britain Sasakawa Foundation for support with grant number 3108, the Royal Society for an international travel grant and the Science and Technology Facilities council, grant D/002400/1 and studentship SF/F005288/1. This research is based on observations with AKARI, a JAXA project with the participation of ESA. M.I. and J.K. were supported by the Korea Science and Engineering Foundation (KOSEF) grant 2009-0063616, funded by the Korea Government (MEST). I.S. acknowledges support from STFC.

Facilities: Akari (JAXA/ISAS).

REFERENCES

- Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, *ApJ*, **686**, 1503
 Broadhurst, T. 1995, arXiv:astro-ph/9511150v1
 Cesarsky, C. J., et al. 1996, *A&A*, **315**, L32
 Chary, R., & Elbaz, D. 2001, *ApJ*, **556**, 562

- Condon, J. J. 1974, *ApJ*, **188**, 279
 Devlin, M. J., et al. 2009, *Nature*, **458**, 737
 Dole, H., et al. 2006, *A&A*, **451**, 417
 Ebbles, T., Ellis, R., Kneib, J.-P., Le Borgne, J.-F., Pello, R., Smail, I., & Sanahuja, B. 1998, *MNRAS*, **295**, 75
 Elbaz, D., Cesarsky, C. J., Chaniai, P., Aussel, H., Franceschini, A., Fadda, D., & Chary, R. R. 2002, *A&A*, **384**, 848
 Elbaz, D., et al. 1999, *A&A*, **351**, L37
 Elíasdóttir, Á., et al. 2007, arXiv:0710.5636v1
 Gardner, J. P., et al. 2006, *Space Sci. Rev.*, **123**, 485
 Granato, G. L., De Zotti, G., Silva, L., Bressan, A., & Danese, L. 2004, *ApJ*, **600**, 580
 Gruppioni, C., Lari, C., Pozzi, F., Zamorani, G., Franceschini, A., Oliver, S., Rowan-Robinson, M., & Serjeant, S. 2002, *MNRAS*, **335**, 831
 Högbom, J. A. 1974, *A&AS*, **15**, 417
 Howell, S. B. 1989, *PASP*, **101**, 616
 Jullo, E., Kneib, J.-P., Limousin, M., Elíasdóttir, Á., Marshall, P. J., & Verdugo, T. 2007, *New J. Phys.*, **9**, 447
 Kneib, J.-P., Ellis, R. S., Smail, I., Couch, W. J., & Sharples, R. M. 1996, *ApJ*, **471**, 643
 Ko, J., et al. 2009, *ApJ*, **695**, L198
 Lagache, G., et al. 2004, *ApJS*, **154**, 112
 Lorente, R., Onaka, T., Ita, Y., Ohshima, Y., Tanabé, T., & Pearson, C. P. 2008, AKARI IRC Data User Manual (ver. 1.4; Kanagawa: ISAS), <http://www.ir.isas.jaxa.jp/AKARI/Observation>
 Metcalfe, L., et al. 2003, *A&A*, **407**, 791
 Murakami, H., et al. 2007, *PASJ*, **59**, 369
 Nakagawa, T. 2004, *Adv. Space Res.*, **34**, 645
 Negrello, M., et al. 2009, *MNRAS*, **394**, 375
 Onaka, T., et al. 2007, *PASJ*, **59**, 401
 Pearson, C. 2005, *MNRAS*, **358**, 1417
 Pearson, C. P., et al. 2007, *Adv. Space Res.*, **40**, 605
 Renault, C., Barrau, A., Lagache, G., & Puget, J.-L. 2001, *A&A*, **371**, 771
 Rodighiero, G., et al. 2006, *MNRAS*, **371**, 1891
 Rowan-Robinson, M. 2009, *MNRAS*, **394**, 117
 Rush, B., Malkan, M. A., & Spinoglio, L. 1993, *ApJS*, **89**, 1
 Serjeant, S., et al. 2000, *MNRAS*, **316**, 768
 Serjeant, S., et al. 2008, *MNRAS*, **386**, 1907
 Smail, I., Ivison, R. J., & Blain, A. W. 1997, *ApJ*, **490**, L5
 Smail, I., Kuntschner, H., Kodama, T., Smith, G. P., Packham, C., Fruchter, A. S., & Hook, R. N. 2001a, *MNRAS*, **323**, 839
 Smail, I., Kuntschner, H., Kodama, T., Smith, G. P., Packham, C., Fruchter, A. S., & Hook, R. N. 2001b, *VizieR Online Data Catalog*, **732**, 30839
 Stetson, P. B. 1987, *PASP*, **99**, 191
 Stetson, P. B. 1990, *PASP*, **102**, 932
 Stetson, P. B. 2000, DAOPHOT2 user's manual
 Teplitz, H. I., Charmandaris, V., Chary, R., Colbert, J. W., Armus, L., & Weedman, D. 2005, *ApJ*, **634**, 128
 Väisänen, P., et al. 2002, *MNRAS*, **337**, 1043
 Wada, T., et al. 2007, *PASJ*, **59**, 515
 Ziegler, B. L., Bower, R. G., Smail, I., Davies, R. L., & Lee, D. 2001, *MNRAS*, **325**, 1571